Smart Patch System (SPS) for Condition Based Maintenance of Rotorcraft Structures

001 Development, Validation, and Demonstration of HUMS Technologies to Detect Cracks and Damages in Rotorcraft Structures and Dynamic Components

Contract # DTFACT-05-C-00022

Review Meeting, June 2006

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Outline

- Background
- FAA project
    - Objectives/Goals
    - Project status
    - Future work
    - Budget and expenditure status

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Introduction

- Monitoring the continued health of aircraft subsystems and identifying problems before they affect airworthiness has been a long-term goal of the aviation industry.

- Structural health monitoring (SHM) offers the promise of a paradigm shift from schedule-driven maintenance to condition-based maintenance (CBM) of assets

  - Built-in sensor networks on the structure can provide crucial information regarding the condition and damage state of the structure.

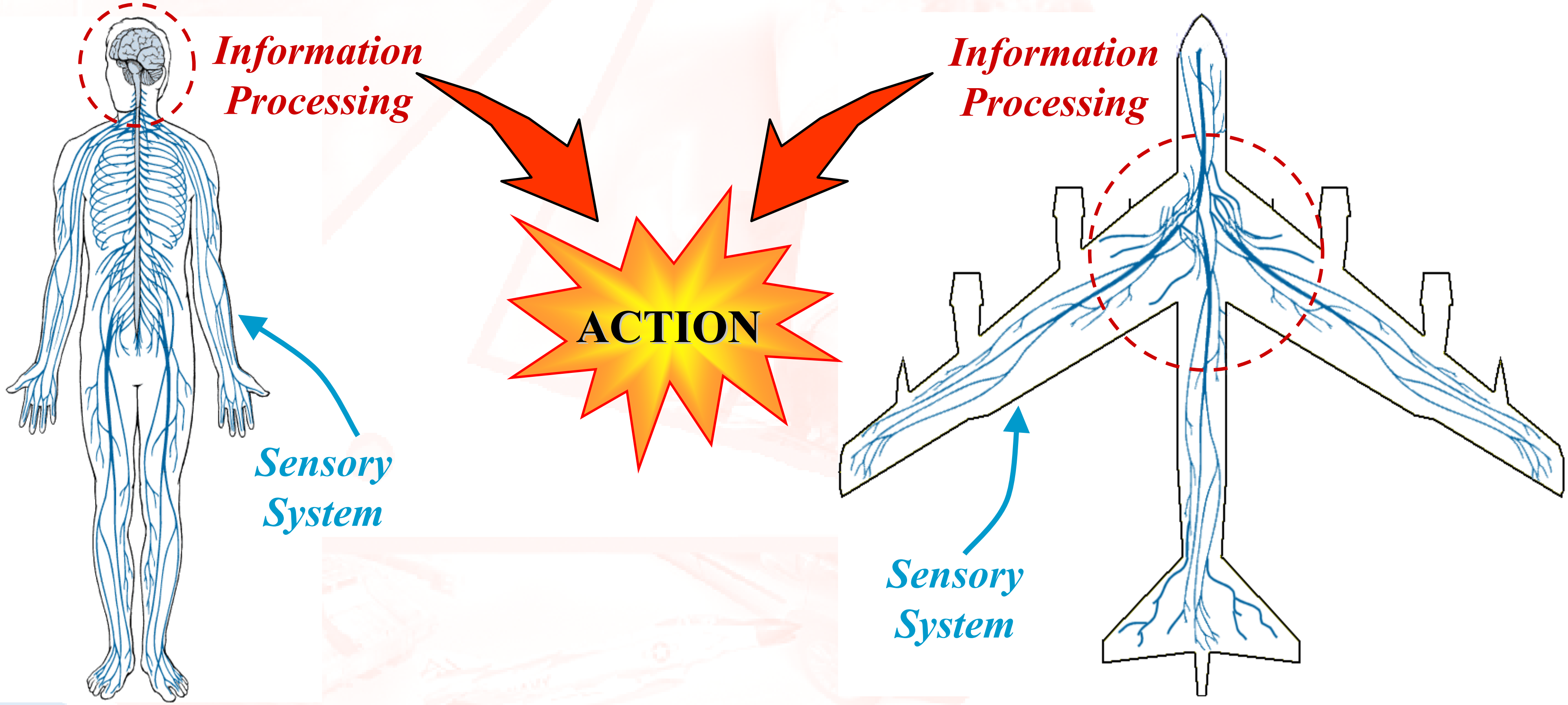
  - Diagnostic information from sensor data can be used for prognosis of the health of the structure and facilitate informed decision processes with respect to inspection and repair, *e.g.*, repair *vs.* no repair or replacement.

About Acellent

Acellent was founded with a mission to provide products and services to customers with complete solutions for **Structural Health Monitoring** in order to:

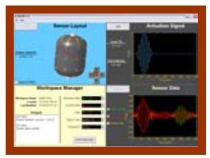
- *Improve reliability and safety*
- *Enhance structural performance*
- *Minimize unnecessary downtime*
- *Reduce maintenance cost*
- *Prolong structural life spans*

SHM Concept/Vision



Benefits

Reduced Inspection costs
- Real-time structural inspection
- Minimum human involvement

Increased Safety
- Monitoring of impacts
- Detect cracks and fatigue damage

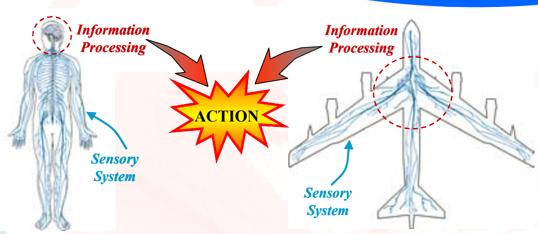
Real-time characterization of structural condition and integrity

Improved processes and procedures for structural life-cycle management and maintenance

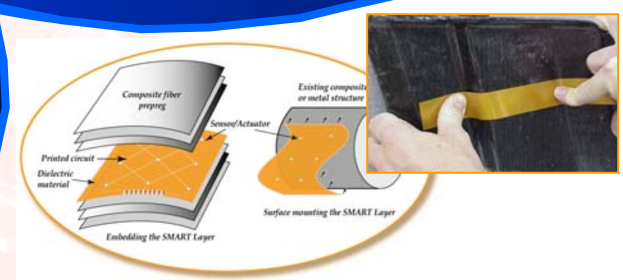
STRUCTURAL HEALTH MONITORING

Condition-based maintenance (CBM) of assets

Capabilities for acquisition, processing and analyzing data generated by embedded systems

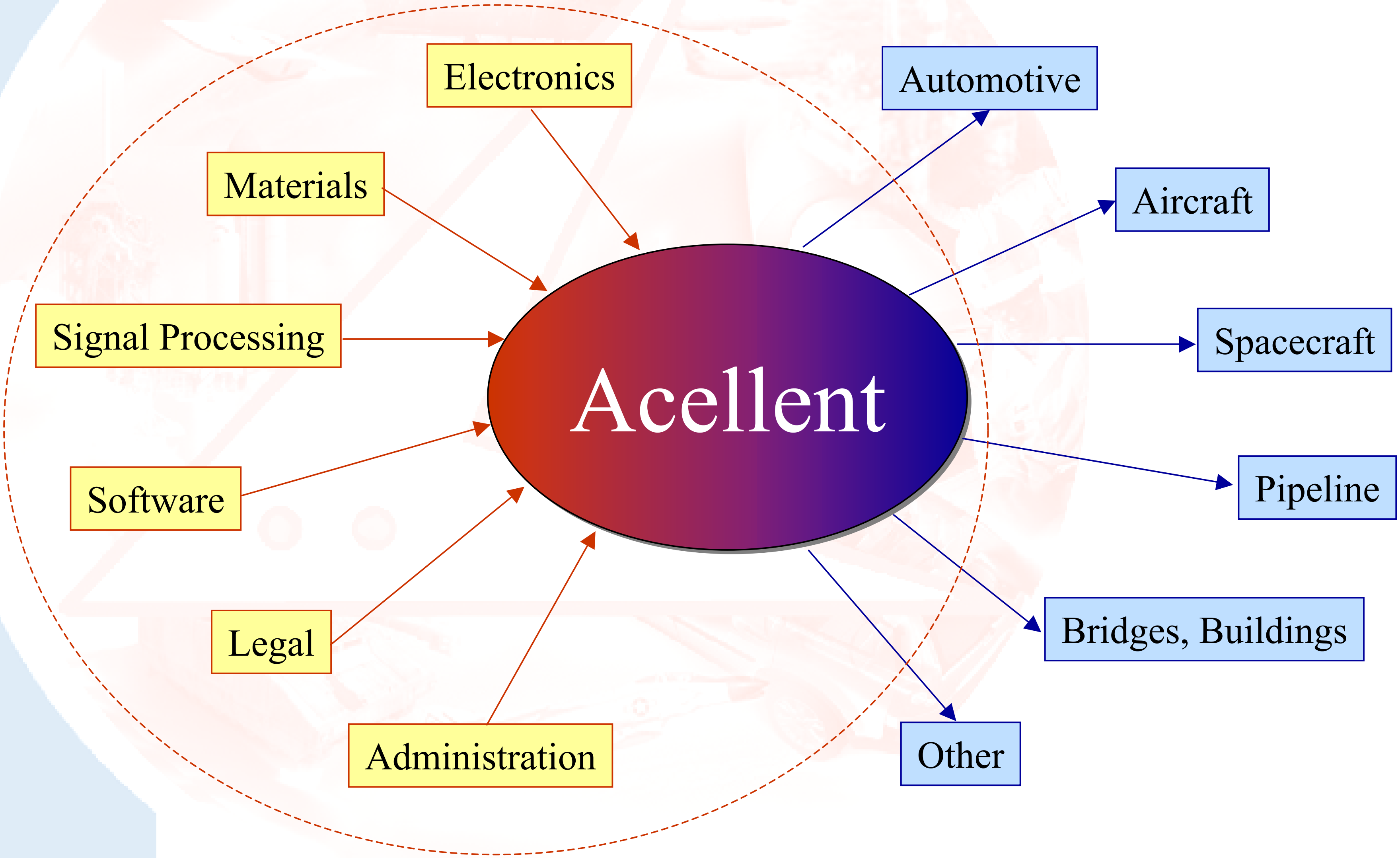


Intelligent Structures
- Integrated sensor networks
- Information processing



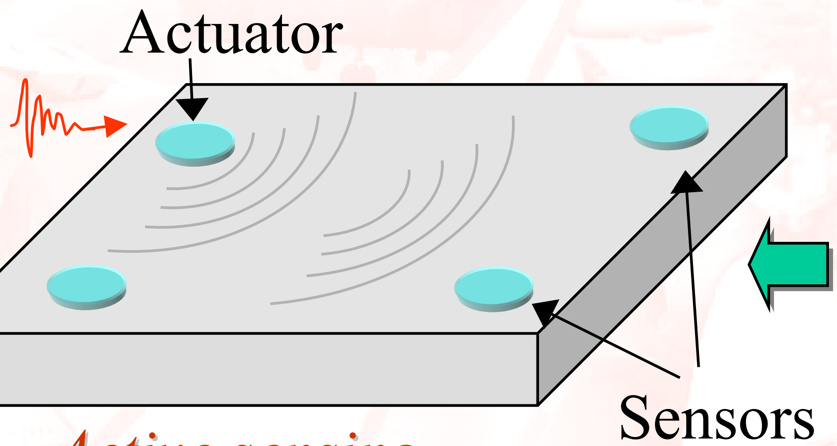
Reduced Downtime
- Monitor inaccessible areas
- Prolong structural life spans

Infrastructure



Piezoelectric Sensor Network

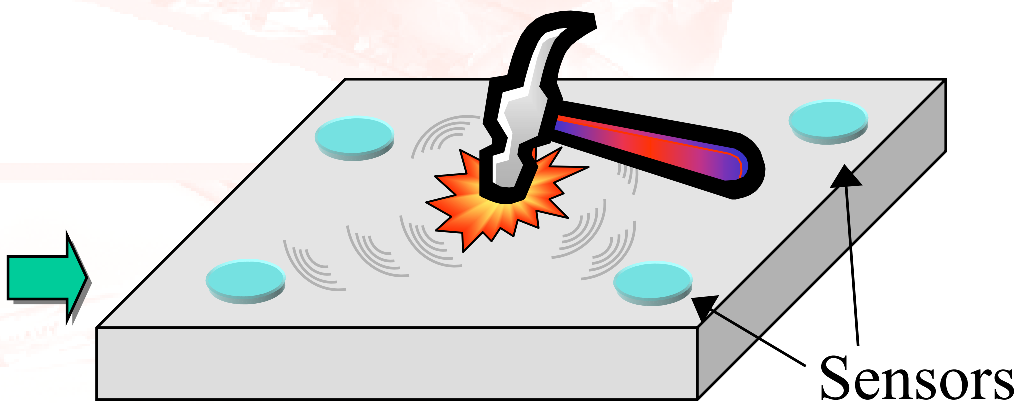
Principle



Active sensing

- Actuators excite structure
- Surrounding sensors record the transient stress waves

- Impacts excite structure
- Sensors record stress waves



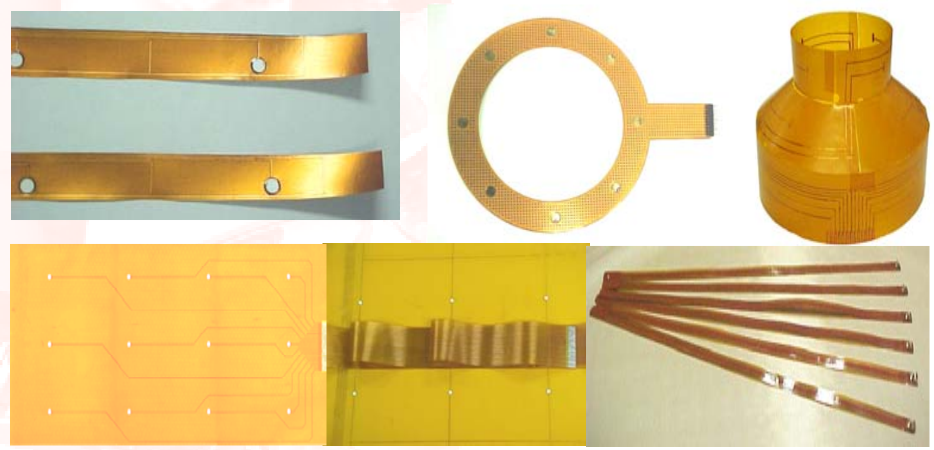
Passive sensing

Acellent's Products

Acellent is providing versatile tools to simplify the SHM process

SMART Layer®

- Thin, flexible sensor carrier
- Easy to install
- Minimized connections
- Multiple sensor types

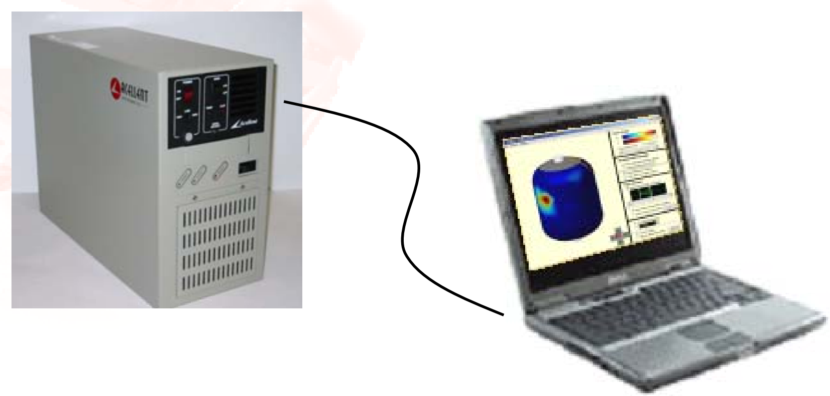


SMART Suitcase

- Portable diagnostic hardware
- Customized form factor

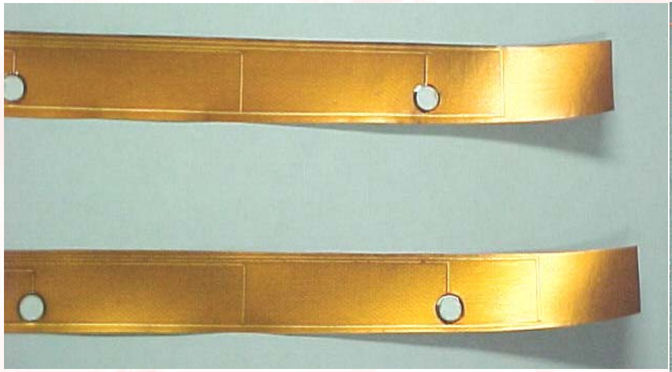
ACESS™ / AIM

- General purpose software suite can be used for any sensor configuration and/or application
- ACESS damage detection software
- AIM impact detection software



ACELLENT technologies, inc

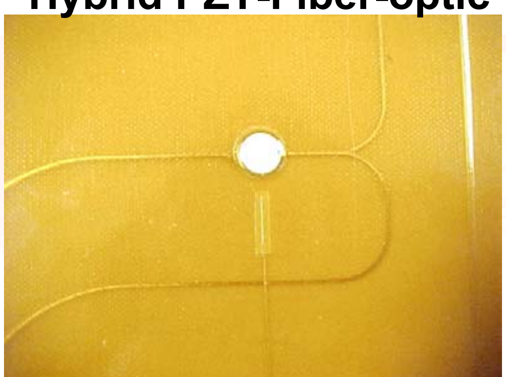
SMART Layers



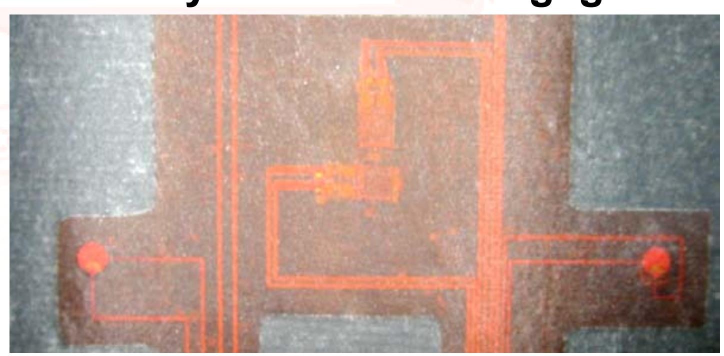
Flexibility

Ease of installation

Hybrid PZT-Fiber-optic



Hybrid PZT-Strain gage



Incorporation of any type of sensors

SMART Suitcase

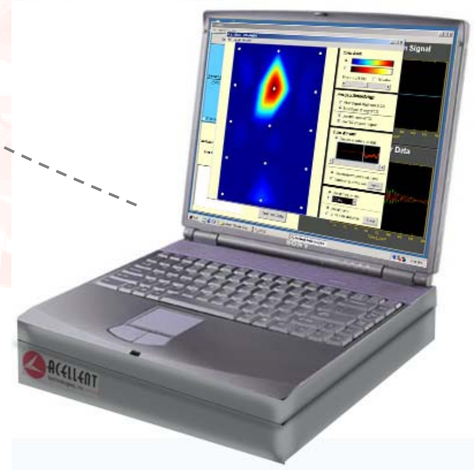
Data acquisition

Signal processing

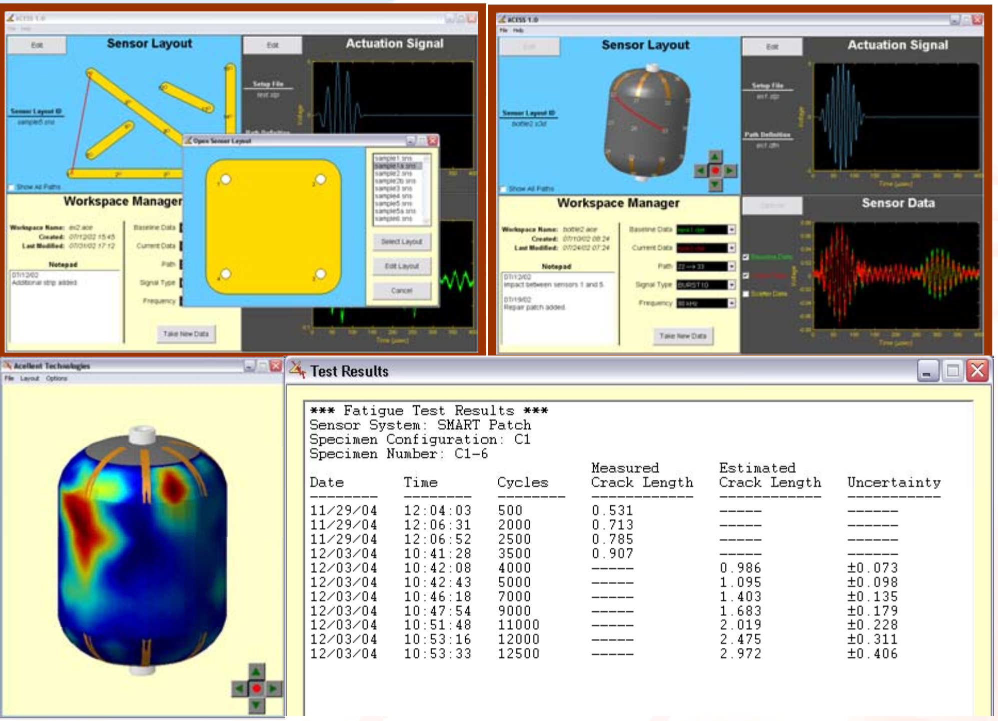
Pulse-Echo mode

Wireless

Large sensor networks



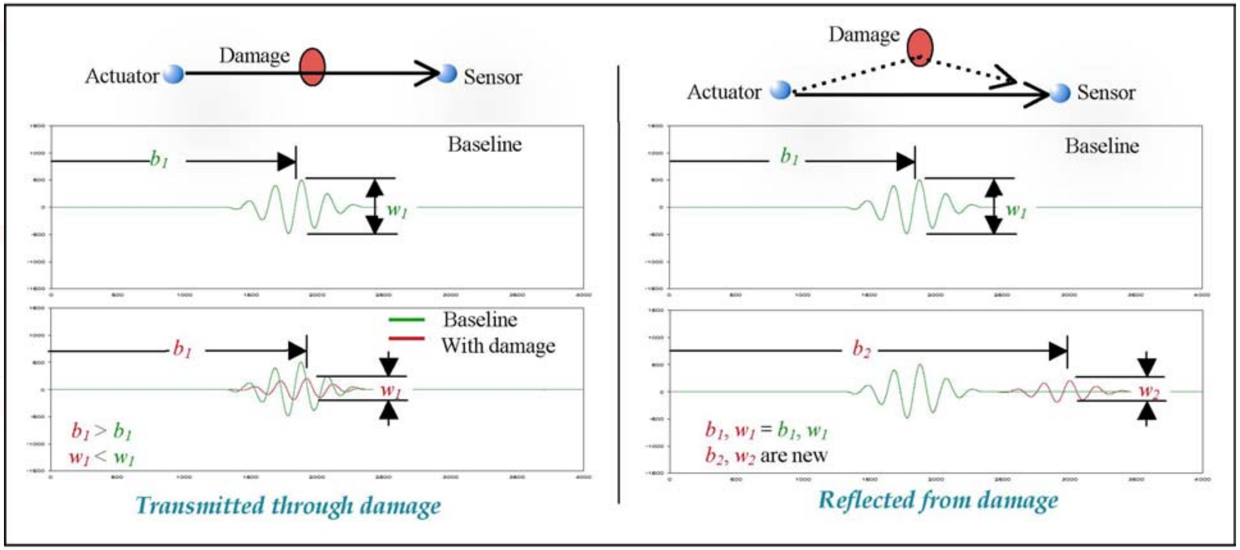
- Location of structural change
- Customized Data Interpretation
  - ✓ Quantification
  - ✓ Relationship to damage



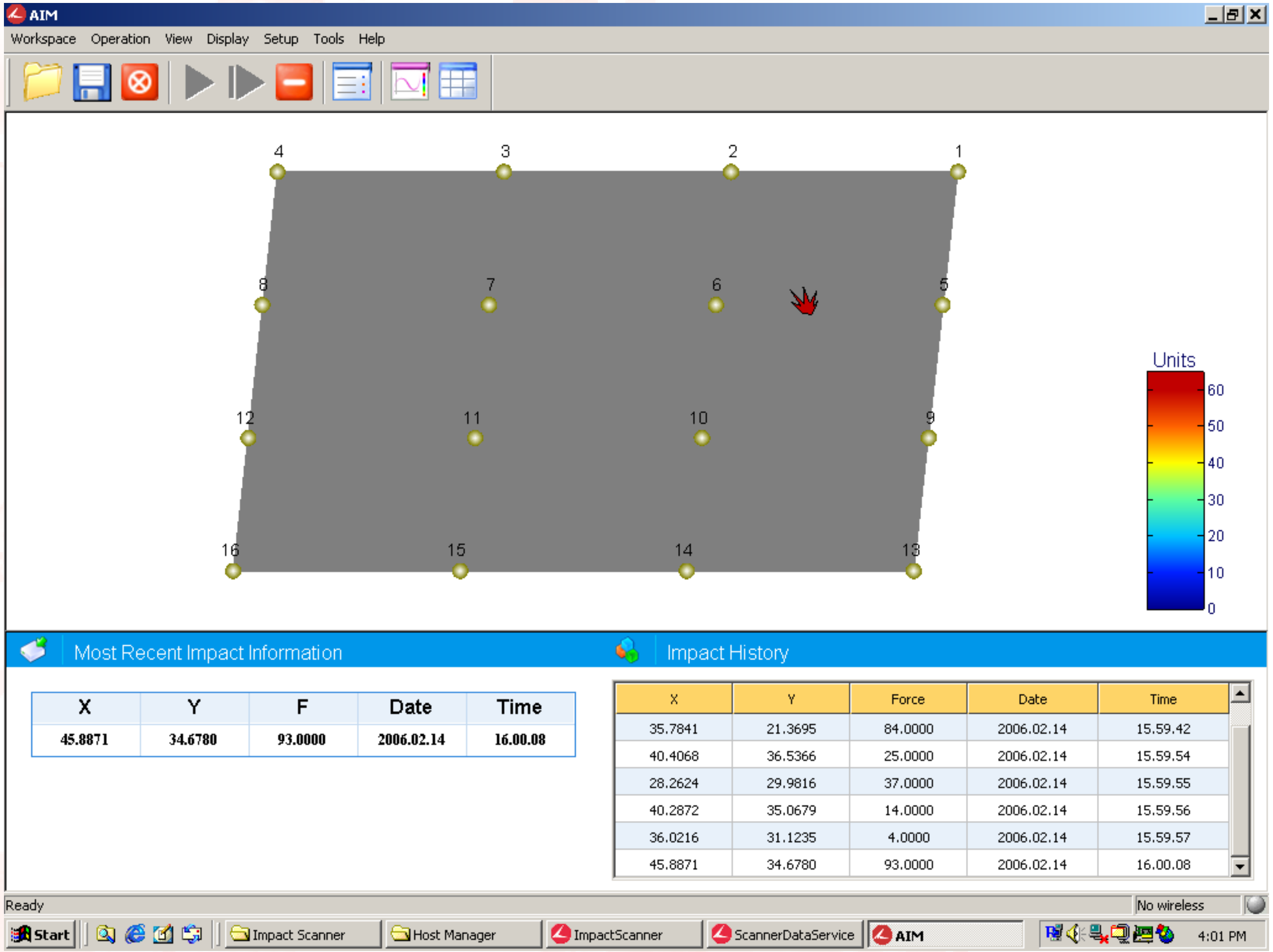
*** Fatigue Test Results ***
Sensor System: SMART Patch
Specimen Configuration: C1
Specimen Number: C1-6

Date	Time	Cycles	Measured Crack Length	Estimated Crack Length	Uncertainty
11/29/04	12:04:03	500	0.531	-----	------
11/29/04	12:06:31	2000	0.713	-----	------
11/29/04	12:06:52	2500	0.785	-----	------
12/03/04	10:41:28	3500	0.907	-----	------
12/03/04	10:42:08	4000	-----	0.986	±0.073
12/03/04	10:42:43	5000	-----	1.095	±0.098
12/03/04	10:46:18	7000	-----	1.403	±0.135
12/03/04	10:47:54	9000	-----	1.683	±0.179
12/03/04	10:51:48	11000	-----	2.019	±0.228
12/03/04	10:53:16	12000	-----	2.475	±0.311
12/03/04	10:53:33	12500	-----	2.972	±0.406

ACESS



AIM



- Real-time sensor data acquisition
- Real-time processing to detect impact location
- Diagnostic image display of impact locations
- Impact force/energy information to predict structure damages

Acellent's SHM systems

System components

SMART Layer®
- Thin, flexible sensor carrier
- Easy to install
- Minimized connections
- Multiple sensor types

Fiber-optics

Piezoelectrics

Strain gages

SMART Suitcase
- Portable diagnostic hardware
- Customized form factor

ACESS™ / AIM

General purpose software suite can be used for any sensor configuration and/or application

System Types

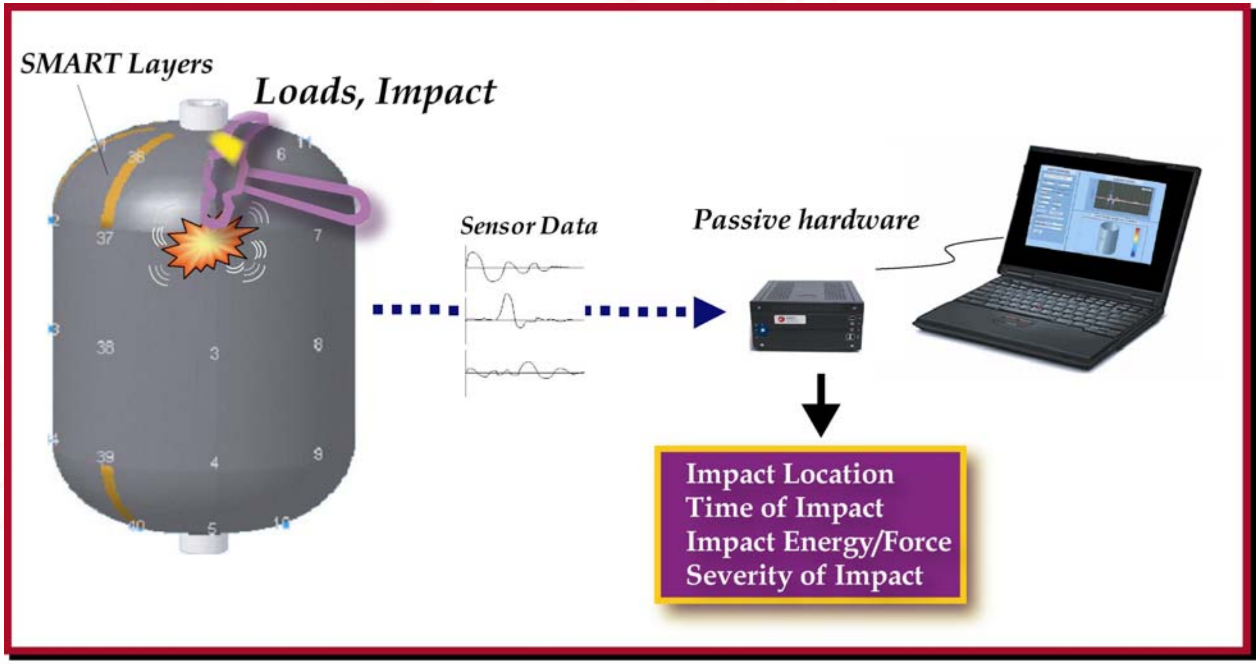
- Passive
- Active
- Passive/Active

SHM systems

- **Passive**
- Active
- Passive/Active

Passive system

- Finds location of impacts
- Records date/time of occurrence
- Determines impact force/energy when calibrated with known impacts
- Wireless

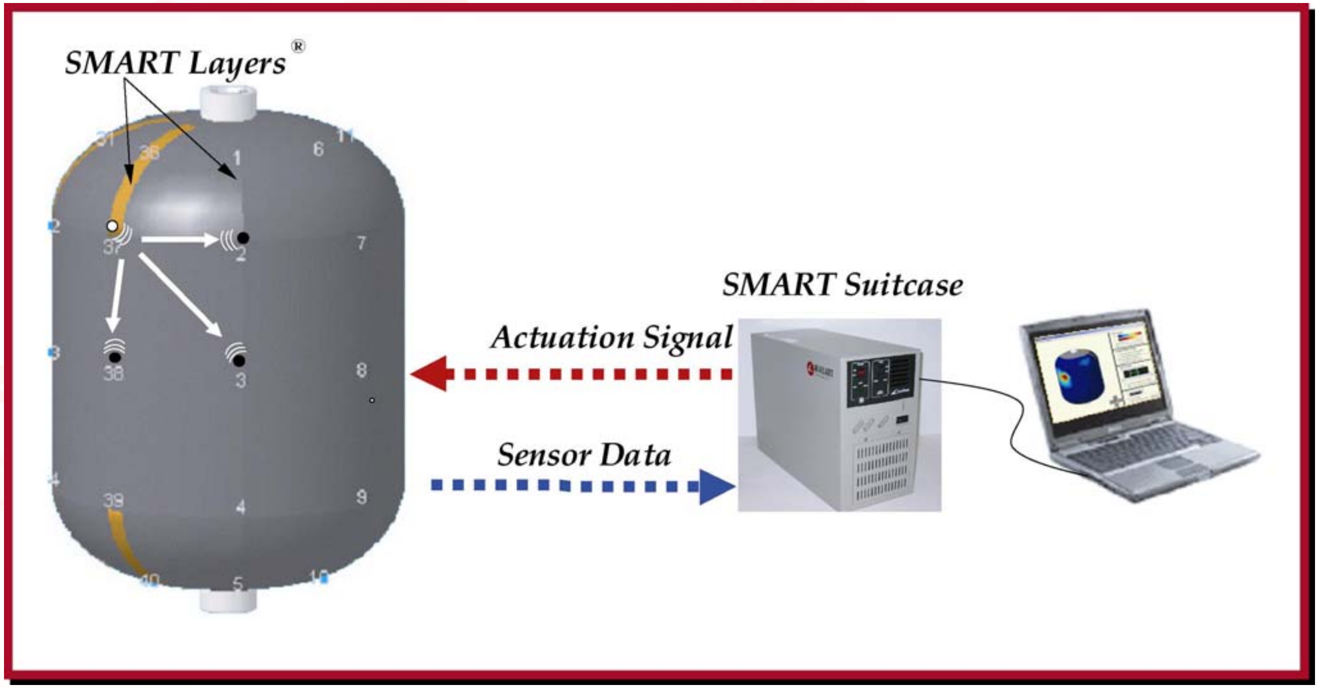


Active system

SHM systems

- Passive
- **Active**
- Passive/Active

- Finds location of structural changes
- Can scan large areas in minutes
- Can identify type/size of damage when calibrated with known damages



SHM systems

- Passive
- Active
- **Passive/Active**

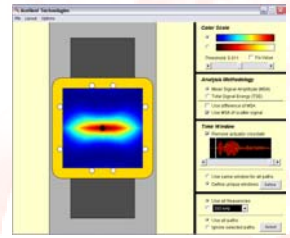
Passive/Active system

- Finds location of impacts
- Quickly (in seconds) determines if impact has caused any structural changes
- Records date/time of occurrence
- Can identify type/size of damage when calibrated with known damages

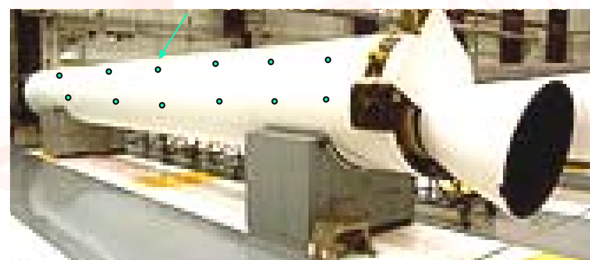
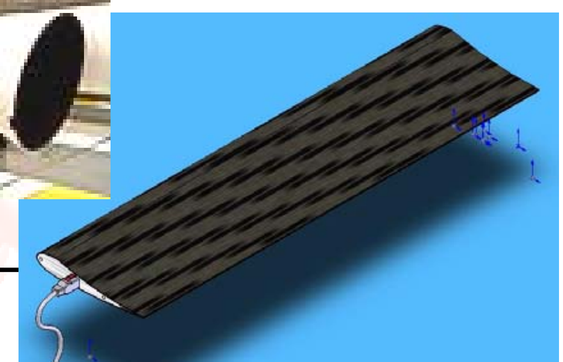
Demonstrations

Applications

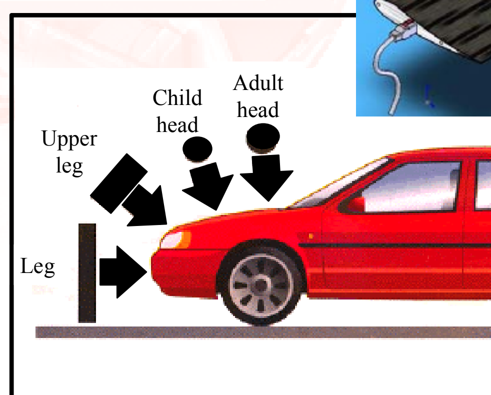
- Hot-spot monitoring
  - *Bonded repairs*
  - *Fatigue cracks*


- Composites
  - *Impact*
  - *Disbond / delamination*

- Smart sensing
  - *Crash sensing*
  - *Other*



Outline

- Background
- FAA project
  - Objectives/Goals
  - Project status
  - Future work
  - Budget and expenditure status

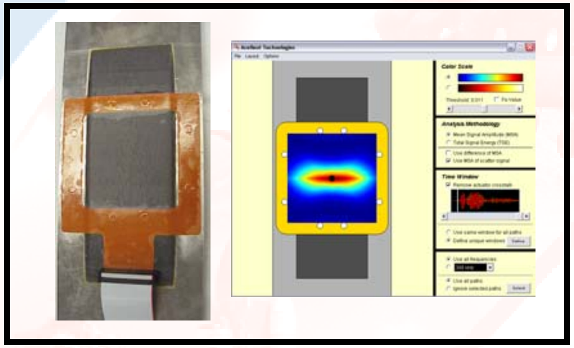
Project goals

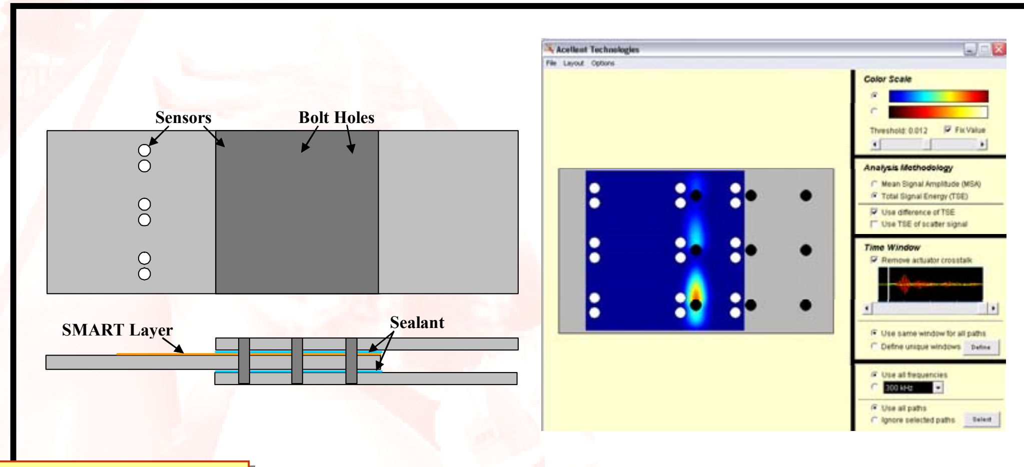
- Develop a Smart Patch System (SPS) that can be used for the in-service monitoring of the health of new and existing rotorcraft structures.
- Provide data for certification of the system for rotorcraft structures as per AC29-2C Section MG-15
- Overall Goals of the system will be to:
  - Reduce the total structural inspection costs for rotorcraft structures
  - Avoid structural failure and catastrophic failures
  - Provide maintenance credit by reducing the number of maintenance activities when the structural condition assessment shows no need of the scheduled work.

Rotorcraft structures

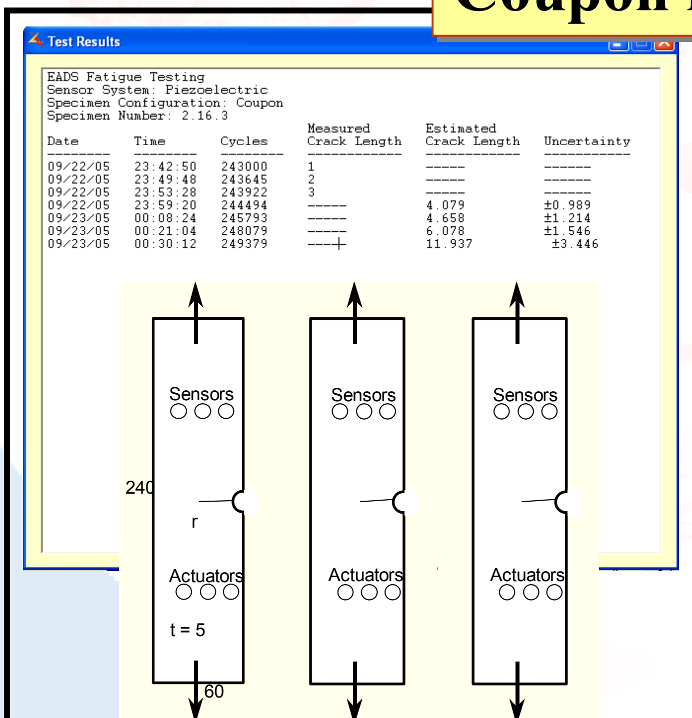
- Typically metal
- Fatigue cracks
- Inaccessible areas
- Dynamic components

Previous developments



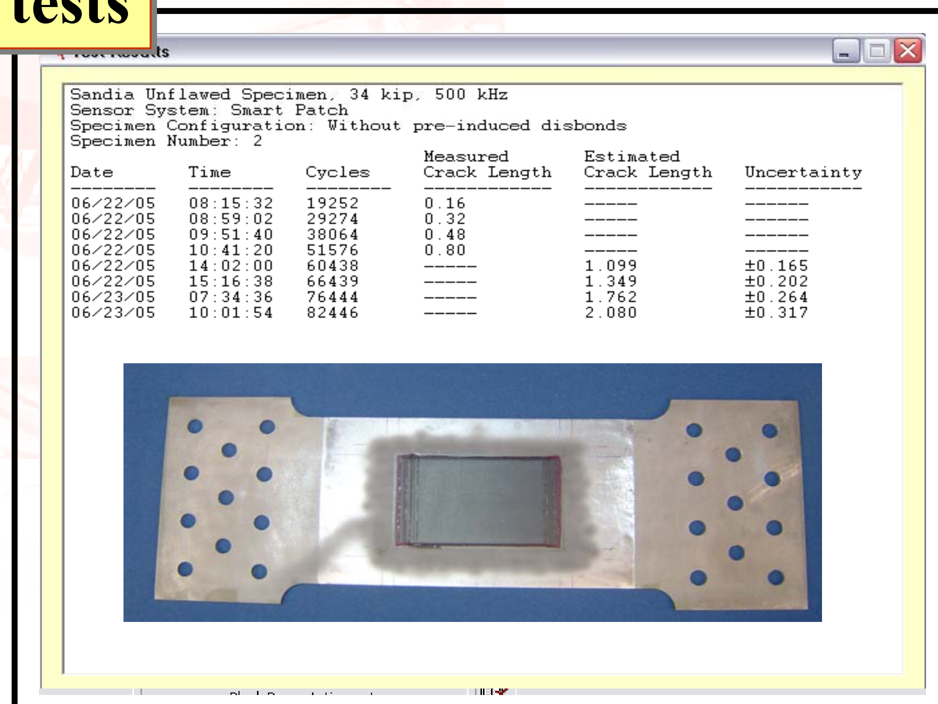


Coupon level tests


Test Results

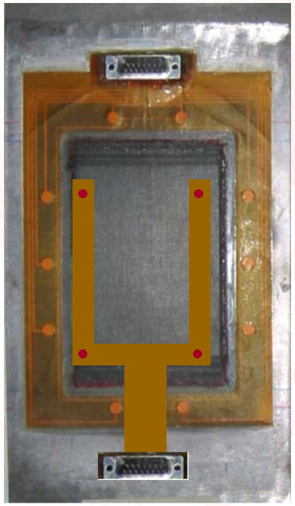
EADS Fatigue Testing
Sensor System: Piezoelectric
Specimen Configuration: Coupon
Specimen Number: 2.16.3

Date	Time	Cycles	Measured Crack Length	Estimated Crack Length	Uncertainty
09/22/05	23:42:50	243000	1	-----	------
09/22/05	23:49:48	243645	2	-----	------
09/22/05	23:53:28	243922	3	-----	------
09/22/05	23:59:20	244494	-----	4.079	±0.989
09/23/05	00:08:24	245793	-----	4.658	±1.214
09/23/05	00:21:04	248079	-----	6.078	±1.546
09/23/05	00:30:12	249379	---+	11.937	±3.446


Sandia Unflawed Specimen, 34 kip, 500 kHz
Sensor System: Smart Patch
Specimen Configuration: Without pre-induced disbonds
Specimen Number: 2

Date	Time	Cycles	Measured Crack Length	Estimated Crack Length	Uncertainty
06/22/05	08:15:32	19252	0.16	-----	------
06/22/05	08:59:02	29274	0.32	-----	------
06/22/05	09:51:40	38064	0.48	-----	------
06/22/05	10:41:20	51576	0.80	-----	------
06/22/05	14:02:00	60438	-----	1.099	±0.165
06/22/05	15:16:38	66439	-----	1.349	±0.202
06/23/05	07:34:36	76444	-----	1.762	±0.264
06/23/05	10:01:54	82446	-----	2.080	±0.317

Damage detection



Composite Doubler with PZT Health Monitoring			
Fatigue Cycles	Measured Total Crack Length	Estimated Crack Length from PZT Sensor Data (0 lbs. load)	Estimated Crack Length from PZT Sensor Data (34 kips load)
Specimen 1 - Unflawed Composite Doubler			
0	0.00		
26,218	0.32	PZT Learning Data	PZT Learning Data
47,000	0.70	PZT Learning Data	PZT Learning Data
67,000	1.50	1.274	1.385
87,000	2.44	1.956	2.367
Specimen 2 - Composite Doubler with Disbond Flaws			
0	0.00		
19252	0.16	PZT Learning Data	PZT Learning Data
29274	0.32	PZT Learning Data	PZT Learning Data
38064	0.48	PZT Learning Data	PZT Learning Data
51576	0.80	PZT Learning Data	PZT Learning Data
60438	1.08	0.981	1.099
66439	1.34	1.35	1.349
76444	1.76	1.567	1.762
82446	2.02	1.909	2.08

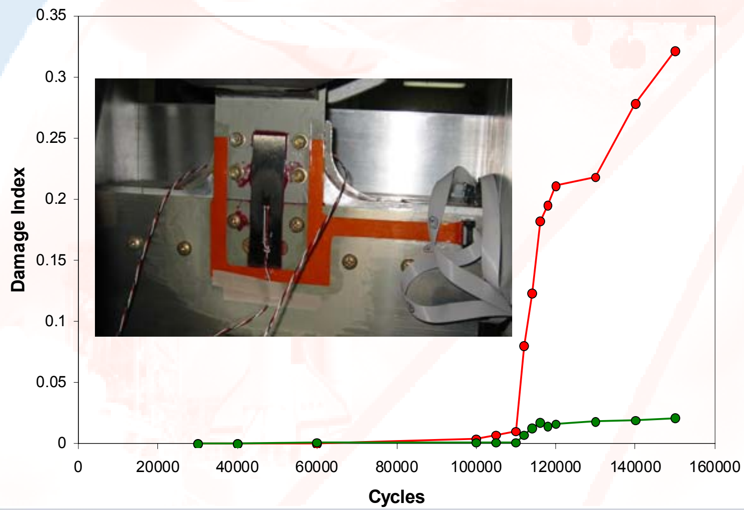
Measurement from visual inspection

Measurement from Acellent's system

Testing conducted with Sandia National Labs

Previous developments

Component level tests



Test Results

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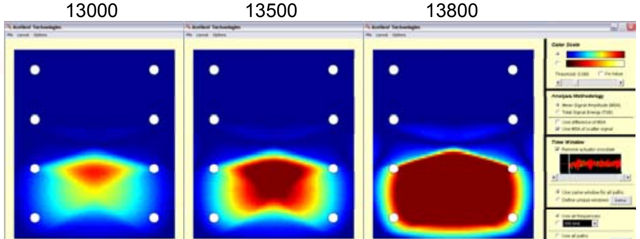
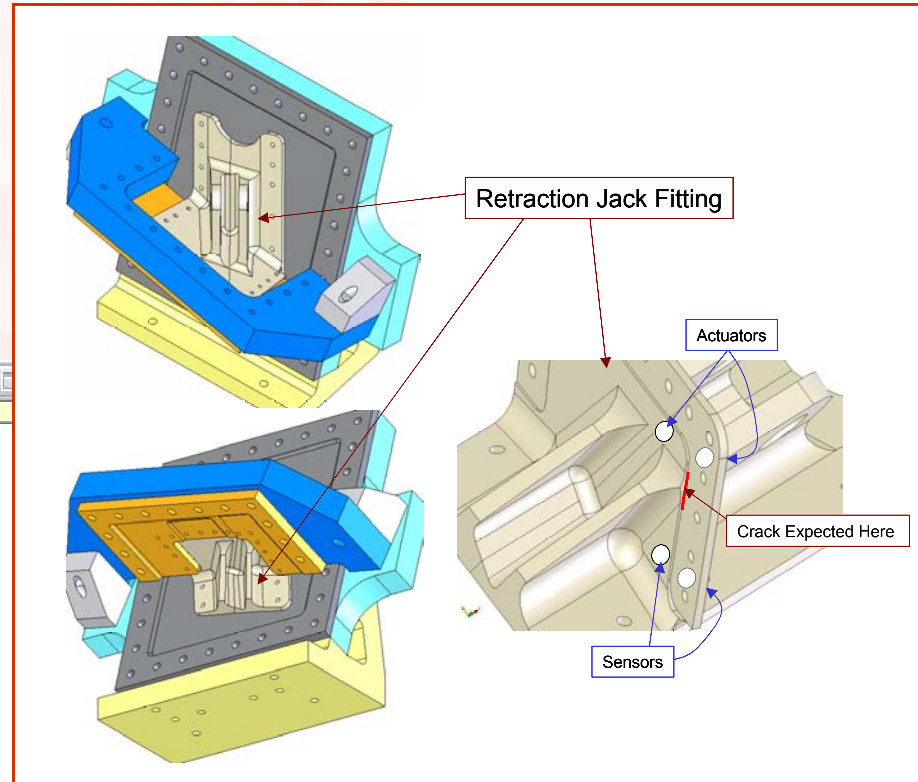
*** SHMBR Component Test Results ***
Sensor System: SMART Layer
Specimen Configuration: Disbond Growth
Specimen Number: 1
```

Date	Time	Cycles	Measured Disbond Area	Estimated Disbond Area	Uncertainty
01/06/05	05:46:52	10500	0.125	-----	------
01/06/05	05:57:46	11000	0.125	-----	------
01/06/05	06:11:14	11500	0.188	-----	------
01/06/05	06:48:26	12000	-----	0.255	±0.151
01/06/05	07:11:38	12500	-----	0.272	±0.170
01/06/05	07:28:12	13000	-----	0.438	±0.360
01/06/05	07:40:32	13500	-----	0.710	±0.672
01/06/05	07:55:10	13800	-----	2.154	±2.545

Cycles →

13000 13500 13800

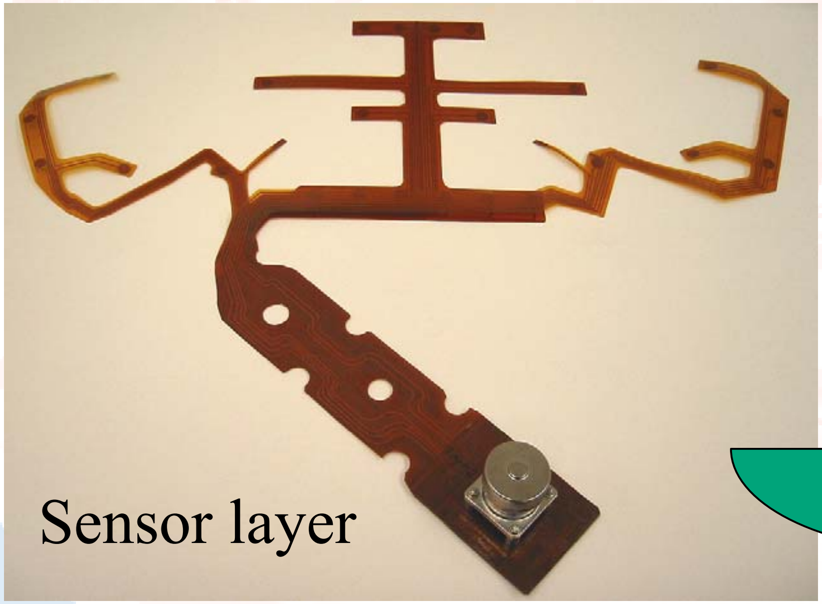




Previous developments

- Installed in February 2006 at Hill AFB
- Flight testing at Luke AFB for approx. 18 months

Flight Testing on F-16



Program Goals

TRL 7+ → **Certification**

Implementation procedures

Testing and validation

SPS system Reliability

Damage detection algorithms

SPS system design

FAA Program

Establish procedures and methodologies for certification of SHM on rotorcraft structures as per per AC29-2C Section MG-15

TRL 5-6

SHM system

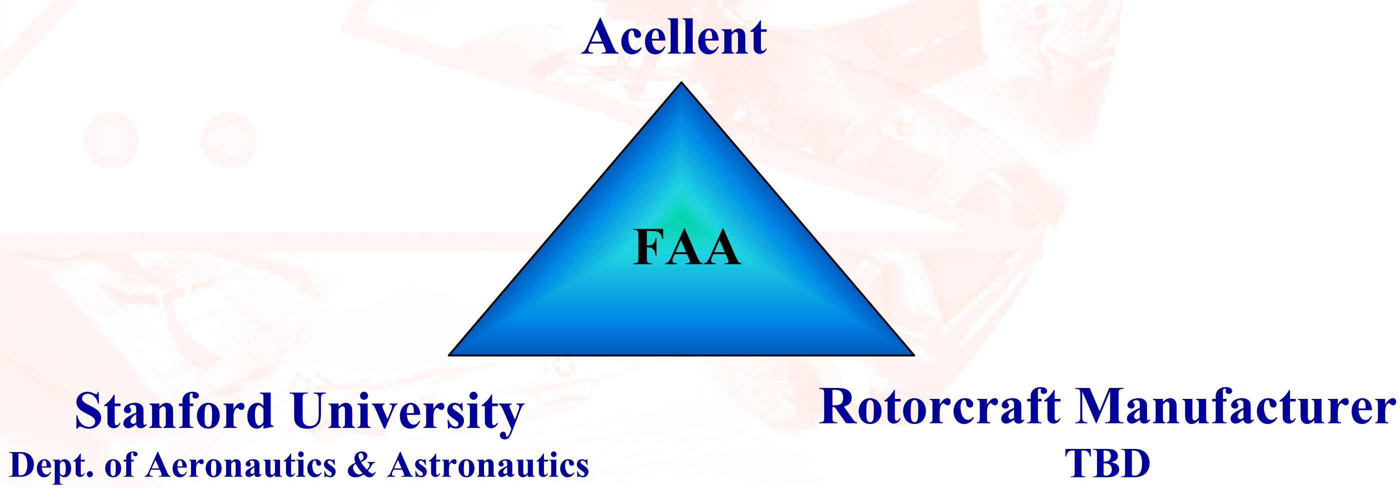
Smart Patch

Hardware

Diagnostic software

Project Information

- 5 year program
- Project start – October 1, 2006
- Kick-off in January 2006
- Currently in Year 1of project



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Program Status

- Smart Patch System Design
  - Sensor Optimization
    - Wave propagation (Stanford)
- Damage Detection Software Development
  - Data management
    - System Architecture
    - Process Flow

SMART Patch System Design

Sensor optimization

Introduction

There are several models that can be used during the design of a structure, however there are few or no models currently available to help design a structure with sensors for the purpose of structural health monitoring.

The primary requirements for the model are:

- Ability to design sensors and simulate wave propagation in a chosen structure
- Ability to model sensors, structures and sensor-structure interaction
- Versatility for use with metal or composite structures
- Ease of use

Introduction

- Stanford has developed a Spectral Element Model (SEM) to analyze structures with built-in piezoelectric-based sensor networks.
- The tool serves two purposes:
  - ✓ to understand fundamentally the interaction not only between diagnostic wave and damages, but also between sensors/actuators and the host structures in ultrasonic frequency ranges; and
  - ✓ to optimize the design of sensor networks for maximizing sensor sensitivity and energy efficiency.
- A spectral element approach is adopted for this purpose.
- The software includes an equation solver and an interface program to link with commercial pre/post-processing software.
- An elasto-dynamic equation solver based on the spectral element method and explicit time integration scheme is also included, which provides an excellent solution convergence in ultrasonic wave propagation problems.
- The solver includes an algorithm to directly solve the coupled electro-mechanical field in piezoelectric materials.
- The interface programs link to commercial finite element-based CAD/ CAE programs to grant access to the geometrical complexity of host structures and to facilitate understanding of the physical phenomena

Introduction

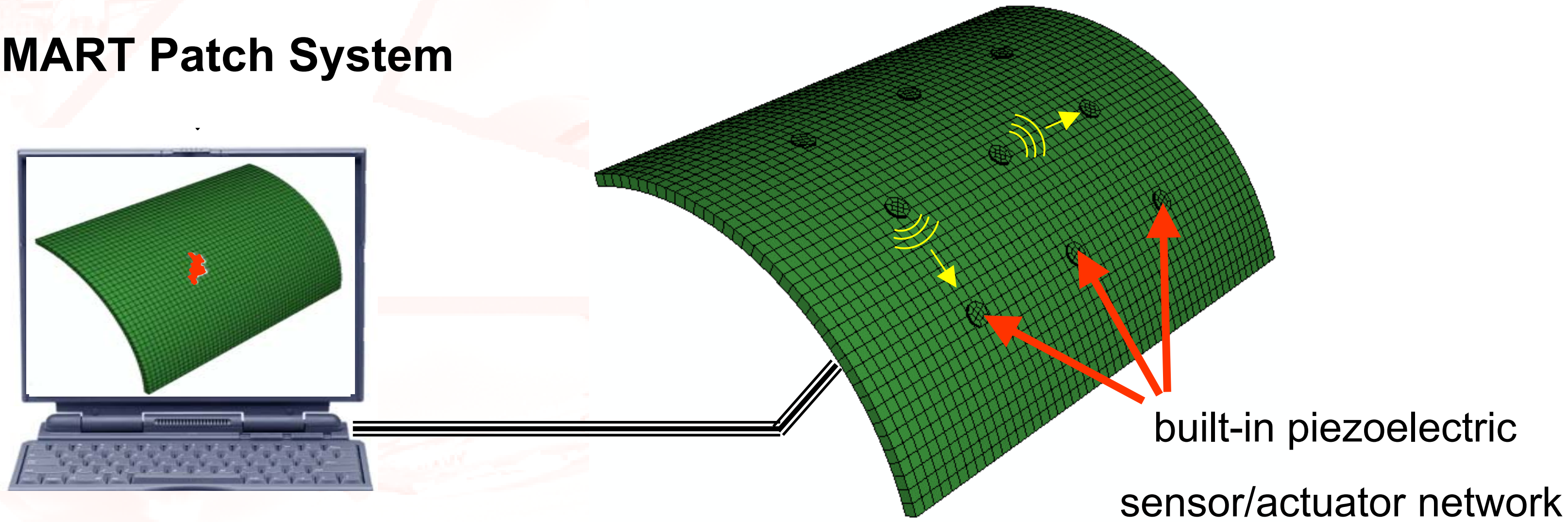
Key innovation for sensor optimization

- fundamental understanding of the complicated wave interactions

Model

- virtual simulation with the aid of computational method

SMART Patch System



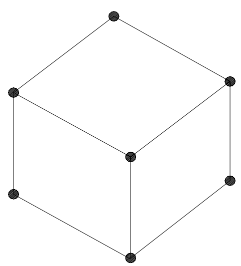
Method of Approach

Spectral Element Method (SEM)

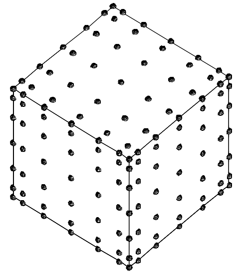
- dividing the domain into pieces (like FEM) + high order polynomial (like Spectral Method) by keeping small the number of elements

Characteristics

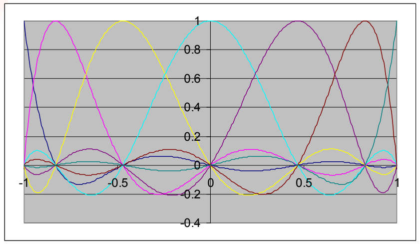
- high order accuracy and computational performance



finite element



spectral element



Lagrange interpolation

Use of the Simulation

- understand interaction between diagnostic wave and damage
- understand interaction between sensor/actuator and structure
- optimize sensor sizes, shapes, locations and excitation signals etc.

SMART Patch Design

Preliminary Results

***aluminum plate**:*

-508mm X 508mm X 1mm

-hole(10mm) & crack(8mm)

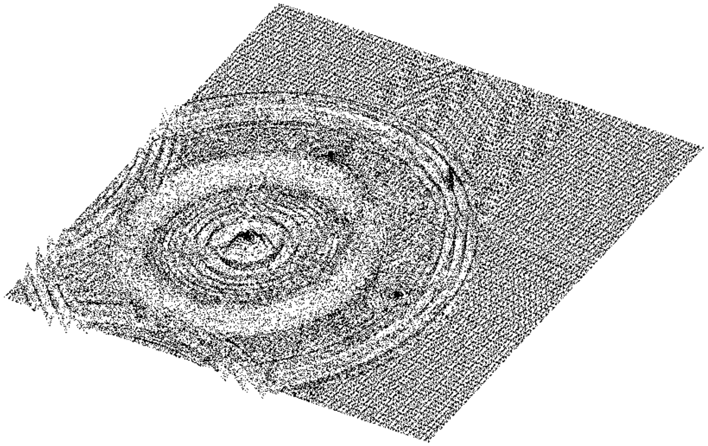
***4 PZT disk sensors**:*

-6.35mm diameter

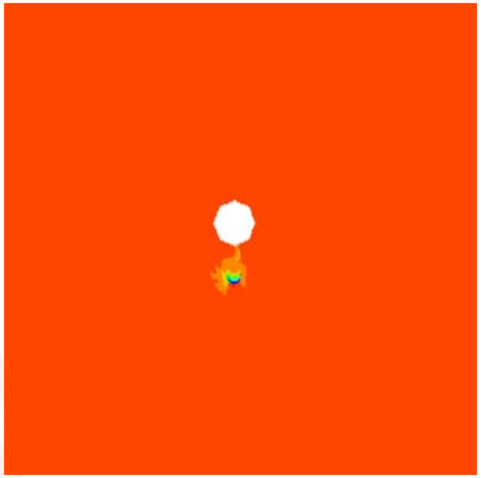
- 0.25 mm thickness

***sine wave actuation**:*

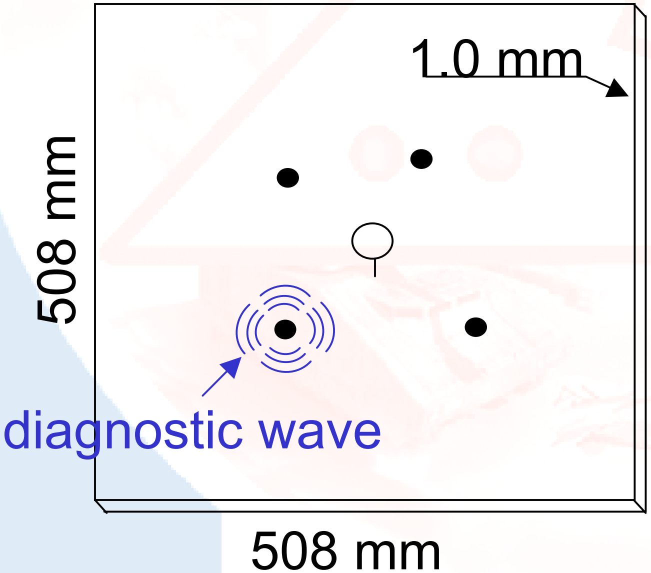
-5 peak/450kHz



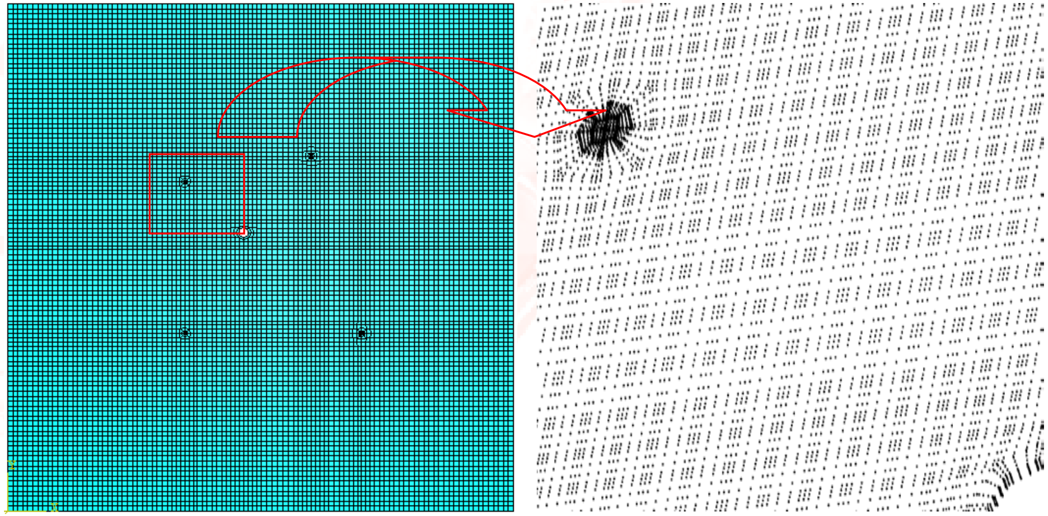
Wave Development 50 μsec



Scatter at the Crack Tip



Geometric Configuration



3D Mesh Configuration

Conclusions

Preliminary Results

- developed spectral element method-based dynamic equation solver
- added algorithm to solve coupled electro-mechanical field in sensors
- showed high performance of the spectral element method-based code
- examined the potential of this code to be integrated with the diagnostic methods for crack detection

Work in Process

- developing the solver & interface programs

Future Work

- optimize sensor design and its network using the code
- integrate with SMART patch design

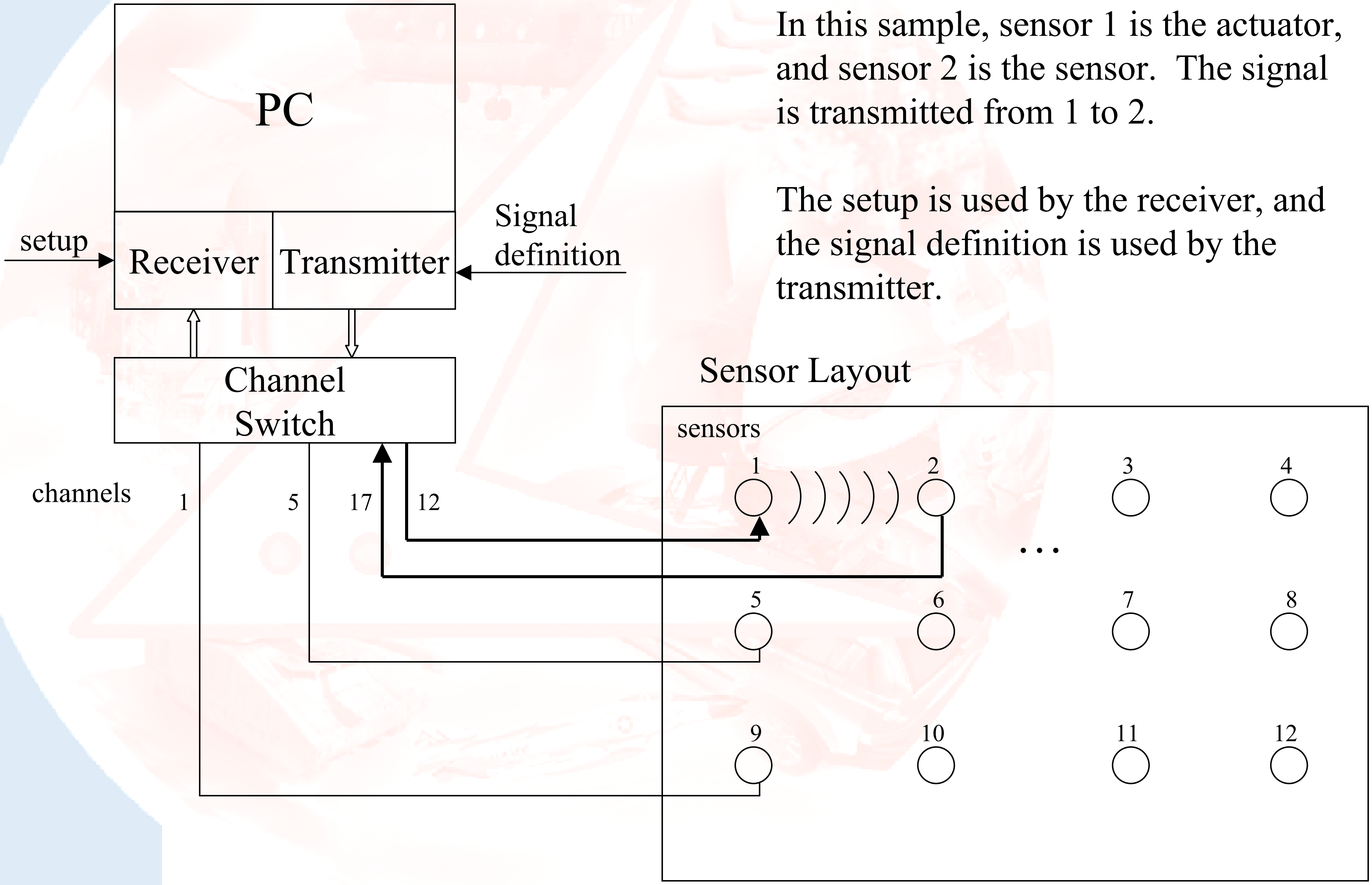
Damage detection software development

Software Architecture

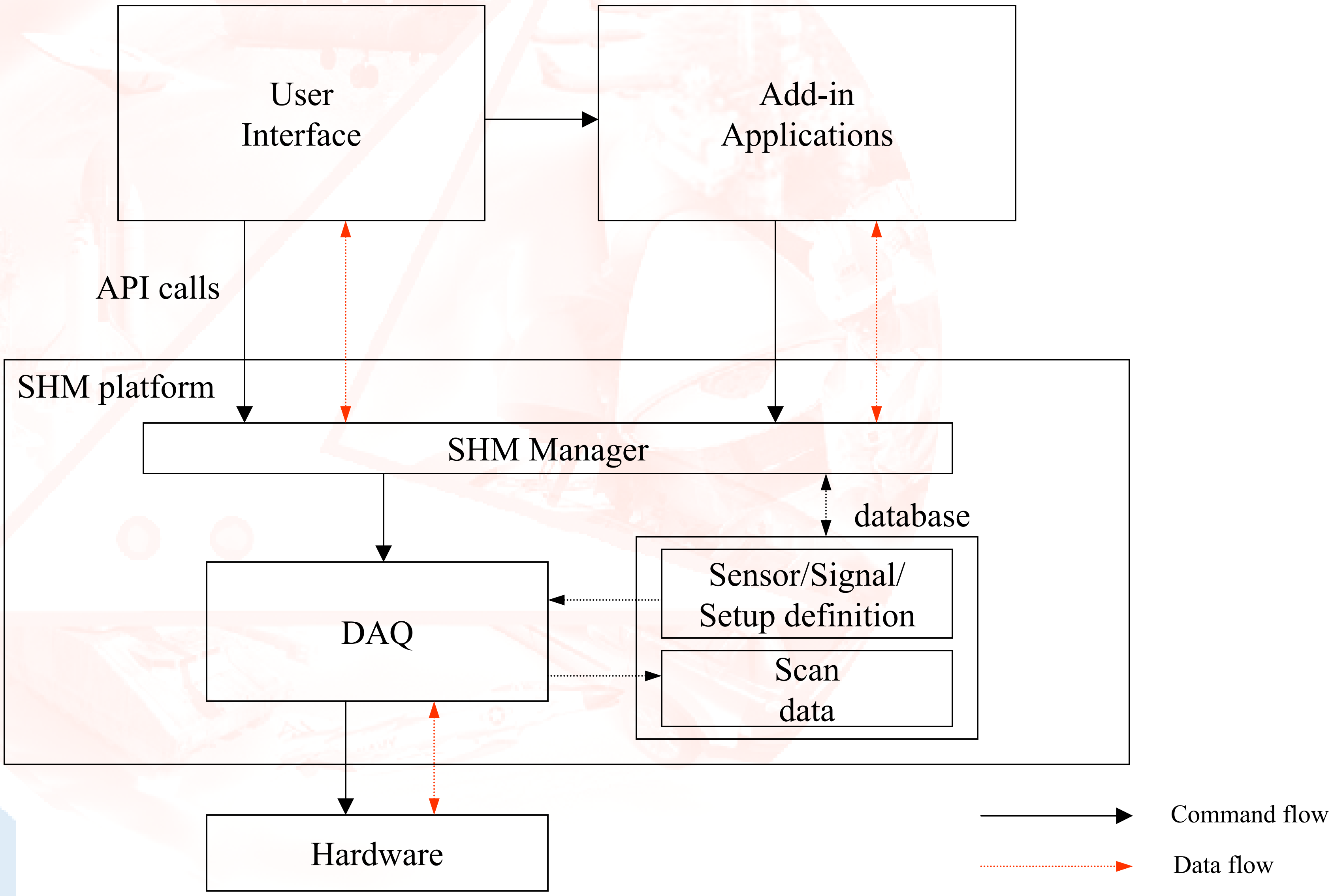
Conceptual system layout

In this sample, sensor 1 is the actuator, and sensor 2 is the sensor. The signal is transmitted from 1 to 2.

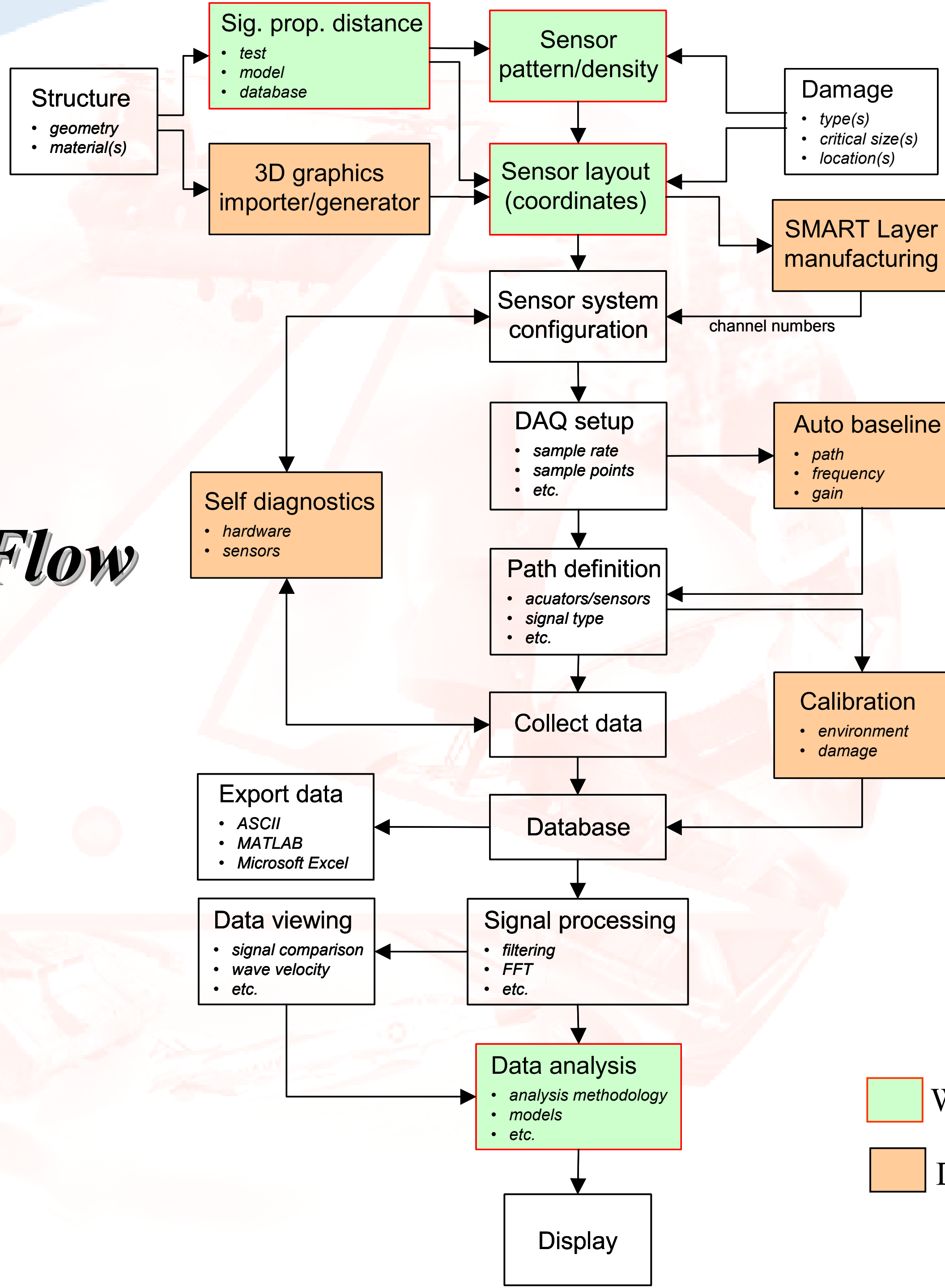
The setup is used by the receiver, and the signal definition is used by the transmitter.



Acellent SHM Architecture



Process Flow



Wave propagation models

Developed with other projects

Outline

- Background
- FAA project
    - Objectives/Goals
    - Project status
    - Future work
    - Budget and expenditure status

Future tasks

Next 6 months

- Smart Patch System Design
  - Continue Sensor Optimization with Stanford
  - Functional Hazards Assessment with rotorcraft manufacturer
  - SMART Patch design
- Damage Detection Software Development
  - Develop data management software
  - Process flow modules

Outline

- Background
- FAA project
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Budget and expenditures status

Total budget	= $1,034,999
Expenditures	= $ 51,941 + $ 36,364 (Stanford invoice pending)
	= $ 88,305
Total Remaining	= $946,694